N88-22418

MODE II FRACTURE MECHANICS

Robert J. Buzzard and Louis Ghosn*
Fatigue and Fracture Branch
NASA Lewis Research Center

ABSTRACT

Current development of high-performance rolling element bearings for aircraft engines (up to 3 million DN, where DN is the product of shaft diameter in millimeters and speed in revolutions per minute) has aroused concern about fatigue crack growth in the inner bearing race that leads to catastrophic failure of the bearing and the engine. A failure sequence was postulated by Srawley (Buzzard et al., 1986), and an analytical program was undertaken (Ghosn, 1988) to simulate fatigue crack propagation in the inner raceway of such a bearing. A fatigue specimen has been developed at NASA (Buzzard et al., 1986) by which fatigue data may be obtained relative to the cracking problems. The specimen may be used to obtain either mode II data alone or a combination of mixed-mode (I and II) data as well and has been calibrated in this regard (Buzzard and Gross, 1988). Mixed-mode fracture data for M-50 bearing steel are presented herein, and a method for performing reversed-loading tests is described (Buzzard, 1988).

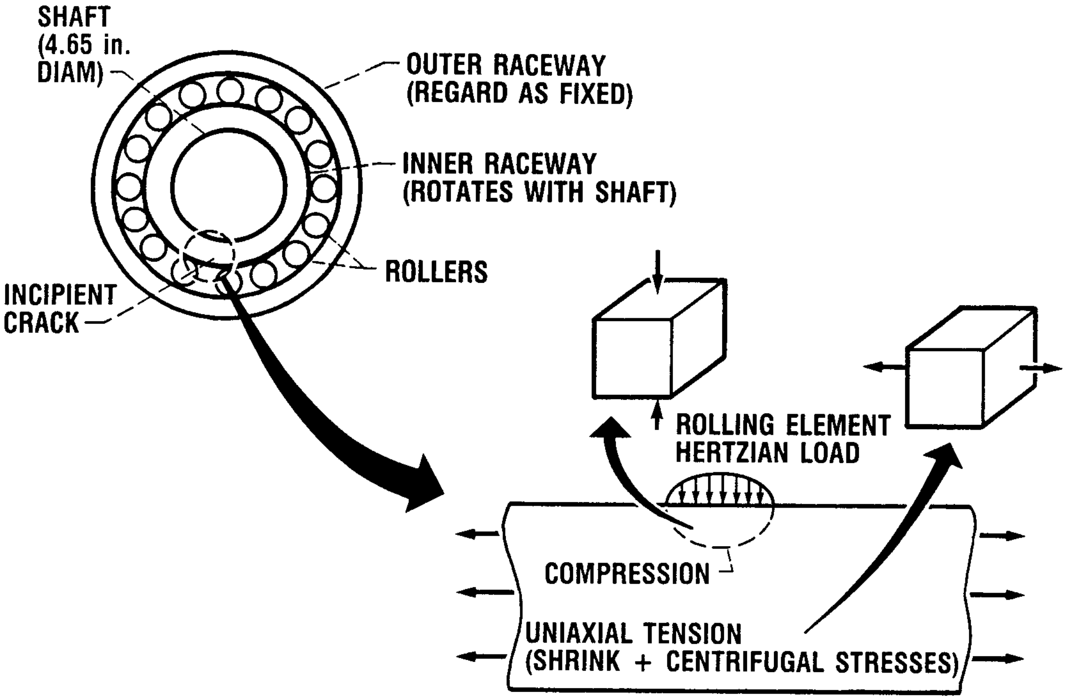
---

*Cleveland State University, Cleveland, Ohio 44115 (work funded under NCC3-46; monitor: John L. Shannon, Jr.) and NASA Resident Research Associate.

OVERVIEW

MODE II MECHANISM AND MODEL

High-performance rolling element aircraft engine bearings may become vulnerable to catastrophic fatigue failure as future requirements push them to ever higher operational limits. A postulated mechanism is described (Buzzard, et al., 1986) and an analytical model developed (Ghosn, 1988).

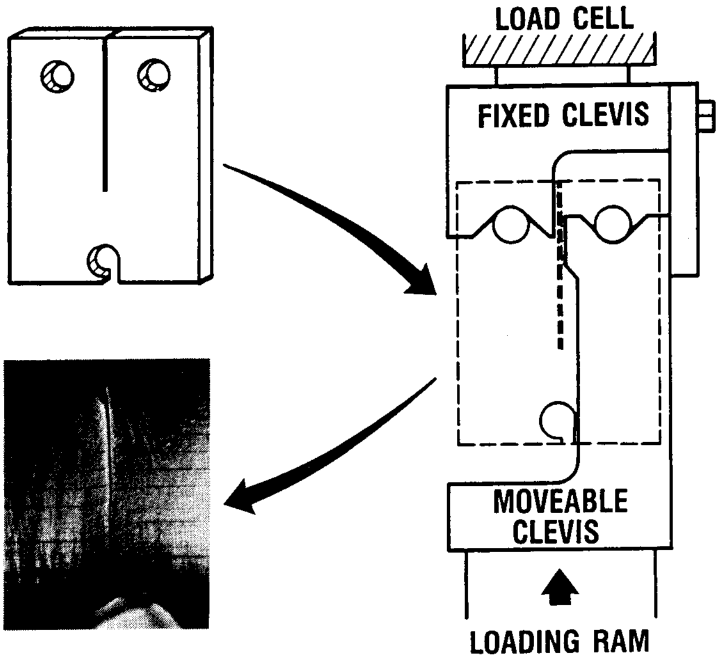


- **ROLLING ELEMENT LOAD IS ADDED TO UNIAXIAL LOAD.**
- **SUBSURFACE VOID FORMS.**
- **CRACK REACHES SURFACE; SURFACE SPALLS.**
- **CRACK GROWS DOWNWARD; RACE FAILS.**

CD-88-31739

MODE II TEST METHOD

A mode II fatigue and fracture specimen and test method have been developed at NASA for use in addressing the potential bearing failure problem (Buzzard et al., 1986). Use of the method has been extended to include mixed-mode testing (Buzzard and Gross, 1988) and reversed load testing (Buzzard, 1988).



CD-88-31740

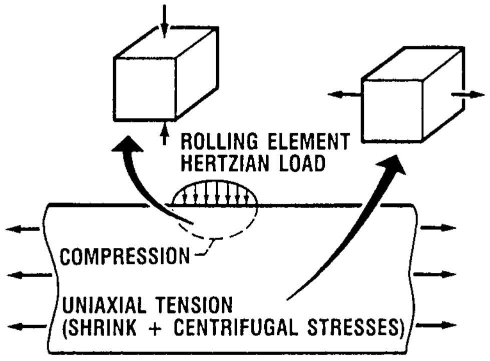
POSTER PRESENTATION

BEARING RACE FAILURE SEQUENCE

High-performance rolling element aircraft engine bearings are being developed for operation at very high rotational speeds (i.e., high DN values). This gives rise to concern regarding possible fatigue cracking of the inner bearing race and subsequent catastrophic failure of the bearing and the engine.

The following basic model was suggested by Srawley (Buzzard et al., 1986). Consider a section of a bearing race in which a location just below the surface is vulnerable to void initiation and growth resulting from the intense shear associated with the passage of individual rolling elements during engine operation. At DN values of about 1.7 million (the present commercial limit) this repetitive loading, in addition to constant hoop stress resulting from centrifugal force and the shrink fit of the race over the shaft, can cause crack growth from the void location to the surface, resulting in a spall. This situation can be monitored by various means and the bearing eventually retired. Under these loading conditions the critical crack size for continued growth is larger than the thickness of the race and therefore further crack growth would not be catastrophic. However, at DN values near 3 million (expected in the near future) the critical crack size is only about 1/5 of the thickness of the race. A small crack may be driven toward this size by alternating mode II stresses as the rolling elements pass by, followed by catastrophic mode I failure when the crack reaches its critical size.

It was primarily to address this problem in the laboratory that a specimen and a loading method were developed at Lewis. The specimen must contain a single notch to simplify data analysis and the monitoring of fatigue crack propagation, and the initial mode I stresses must be insignificant in comparison with the mode II stresses. Self-similar crack growth under mode II loading is desired but is obtainable only for structural materials that are less brittle than hardened bearing steel. Fatigue data for materials that do not exhibit self-similar crack extension must be analyzed in mixed-mode terms.



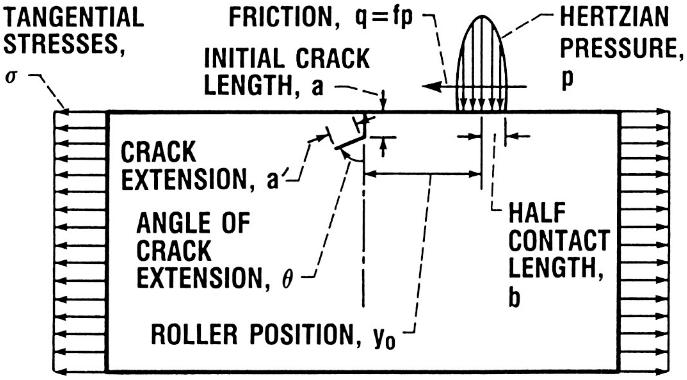
- **ROLLING ELEMENT LOAD IS ADDED TO UNIAXIAL LOAD.**
- **SUBSURFACE VOID FORMS.**
- **CRACK REACHES SURFACE; SURFACE SPALLS.**
- **CRACK GROWS DOWNWARD; RACE FAILS.**

CD-88-31741

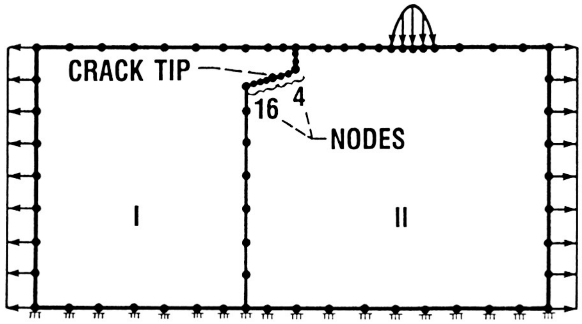
NUMERICAL SIMULATION

An analytical program was undertaken to simulate fatigue crack propagation in the inner raceway of high-speed bearings (Ghosn, 1988). The analysis makes use of the boundary integral method with a multidomain formulation. The multidomain formulation allows the two faces of the crack to be modeled in two different subregions, making it possible to analyze crack closure when the roller is positioned on or close to the crack tip. The stress intensity factors K_I and K_{II} along any direction are computed. These calculations permit determination of the crack growth direction along which the crack driving force is maximum. For brittle materials the fatigue crack driving force is the alternating K_I, but since the mean stress intensity is not constant during the loading cycle, the alternating K_I is an insufficient parameter. The mean stress effect is corrected for by assuming the crack driving force to be the product of the mean times the alternating K_I.

LOADING SIMULATION OF INNER RACEWAY



MULTIDOMAIN BOUNDARY INTEGRAL MESH



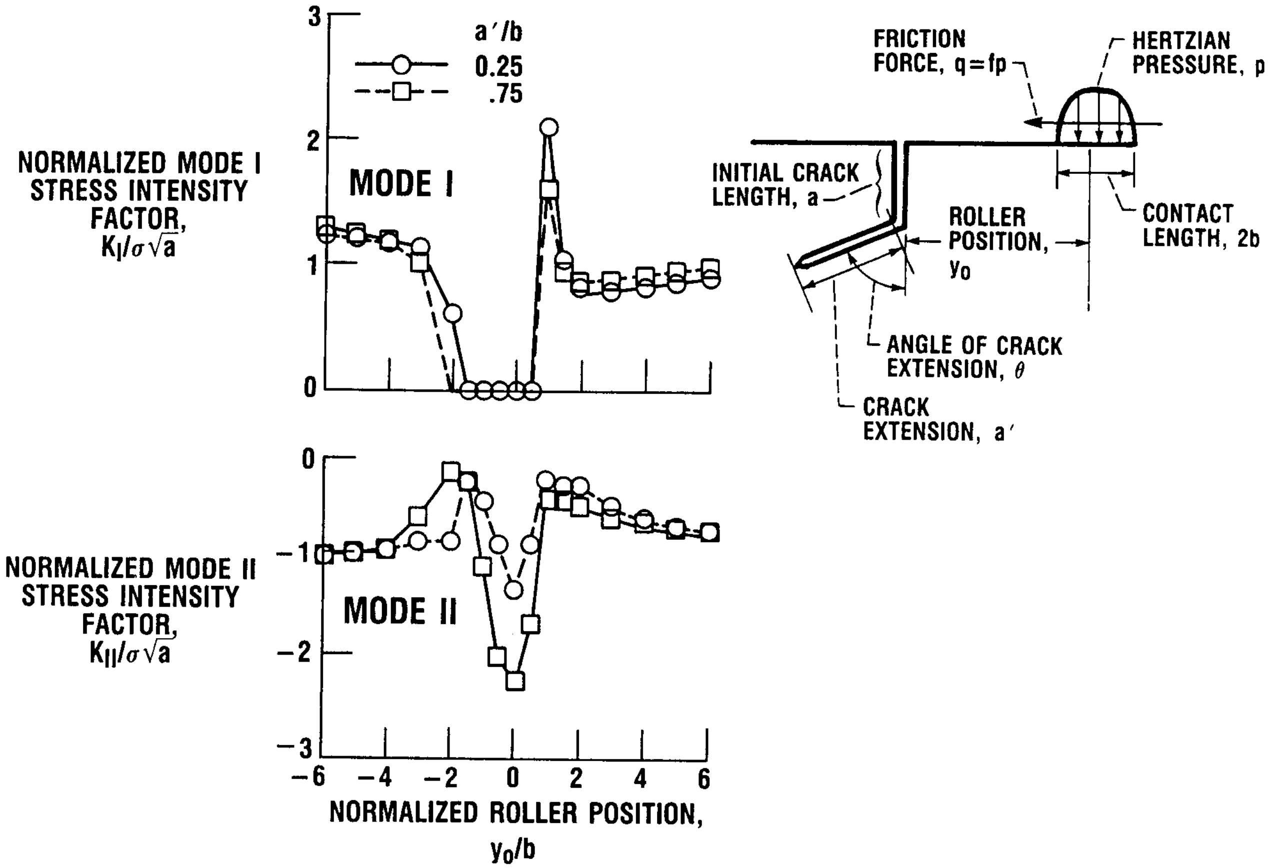
ACTUAL CRACK PROFILE IN INNER RACEWAY OF HIGH-SPEED BEARINGS

CD-88-31742

STRESS INTENSITY FACTOR VARIATIONS

The crack extension in a high-speed bearing was simulated numerically by using the multidomain boundary integral equation method (Ghosn, 1988). The graphs show typical variations of the normalized mode I and mode II stress intensity factors (K_I/σ a and K_{II}/σ a, respectively). An original straight crack, a/b = 1.0, was extended in the direction of the maximum crack driving force. For a/b = 1.0, the maximum crack driving force was along an angle θ equal to 71°. As the Hertzian load passed over the crack, the stress intensity factors, K_I and K_{II}, decreased and then increased. These variations in K_I and K_{II} can result in a fast-growing crack in the inner raceway that can cause the complete failure of the bearing.

TYPICAL VARIATION OF STRESS INTENSITY FACTORS WITH ROLLER POSITION FOR KINKED CRACK (a/b=1.0, θ=71°, f=0.2)



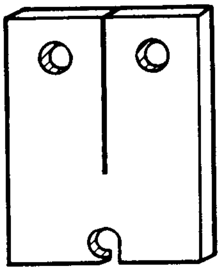
CD-88-31743

MODE II TEST METHOD

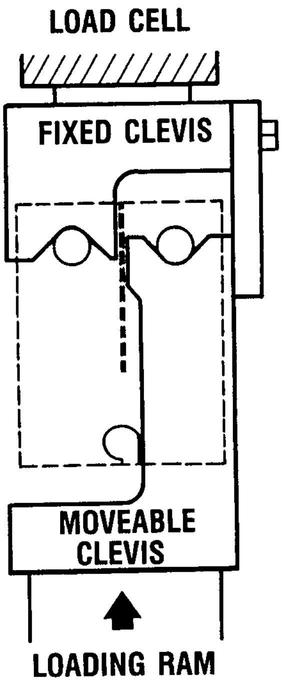
A novel mode II test specimen and testing fixture have been developed at Lewis that may aid in understanding phenomena associated with mixed-mode fatigue failures in high-performance aircraft engine bearing races (Buzzard et al., 1986 and 1987). The specimen contains one single-ended notch, which simplifies data gathering and reduction; the fatigue crack grows in-line with the direction of load application in many engineering materials; a single-axis test machine is sufficient to perform testing; and the mode I component can be practically eliminated if so desired.

The figure shows the shape of the specimen and the testing fixture/loading method. As a compressive load is applied, relative movement of the clevises causes a shearing force to be applied to the specimen along the loading axis. Rotation of the specimen is prevented by the lower loading pin.

The specimen has been calibrated (Buzzard and Gross, 1988) and analyzed by photoelastic and finite element methods (Gross et al., 1986).



SPECIMEN



LOADING METHOD

CD-88-31744

MODE II FRACTURE PATH

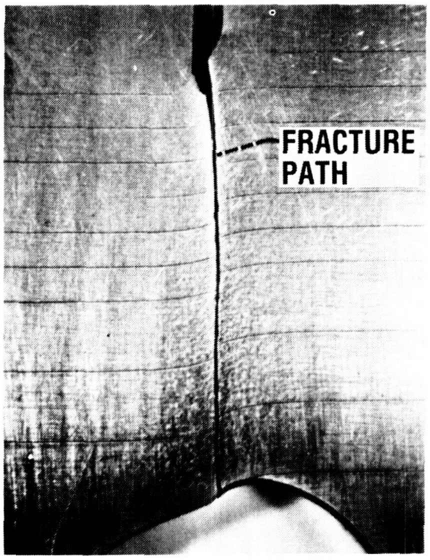
Mode II fracture and fatigue tests have been performed for hardened M-50 bearing steel and for less brittle engineering materials (steels and aluminum alloys). Under identical loading conditions the fatigue and fracture paths for the two classes of materials are quite different, as shown below for the test zone of a specimen of each class.

The fracture and high-load fatigue crack path for an aluminum engineering alloy is shown (in the photograph on the left) to extend in-line with the axis of major load application. It is reasoned that relative displacement of the two specimen halves along the loading line, promoted by plasticity and possible void growth at the crack tip, contribute to this observed behavior. At low fatigue loads, however, the crack proceeds in a direction of about 70° toward the tensile-loaded leg of the specimen (crack not shown). This direction is predicted by the maximum tangential stress and minimum strain energy criteria. The "threshold" load responsible for the difference in behavior has yet to be investigated more thoroughly (Buzzard et al., 1986).

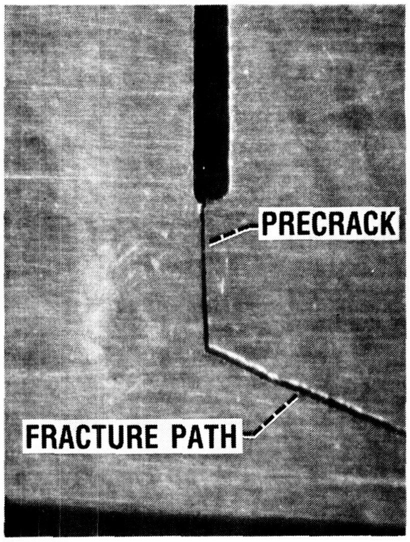
The fracture and fatigue path at both high and low loads for the brittle bearing steel (shown in the photograph on the right) extends only in the direction of about 70° from the tip of the precrack toward the tensile-loaded leg of the specimen, as predicted by theory.

This "dual" behavior suggests that the type of material, the loading restraints affecting structural mobility, and the magnitude of the load, in addition to the possibility of plasticity or void growth at the crack tip, must be given consideration when analyzing the direction of mode II crack progression.

ALUMINUM ALLOY



BEARING STEEL



CD-88-31745

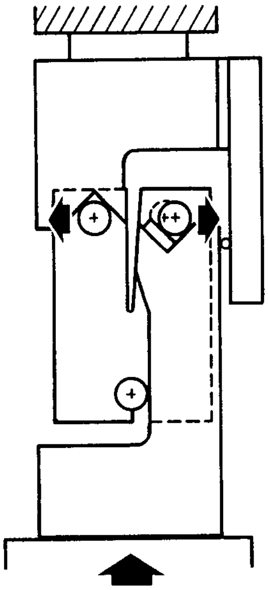
MIXED-MODE AND REVERSED-LOAD TEST METHODS

Mixed-mode (I and II) testing, wherein the mode I component is fixed and the mode II component is variable, may be accomplished with the NASA mode II test system (Buzzard and Gross, 1988). Spacers are placed beneath one of the loading pins as shown on the left. Application of a compressive load causes this loading pin to move outward (or inward, if desired) by a fixed distance determined by the thickness of the spacers. This distance is monitored by a standard ASTM clip gage, which spans the specimen along the loading pins' horizontal centerline. As the moving pin becomes seated in the vee-notch, lateral movement ceases and further load application results in loading in the shear direction only.

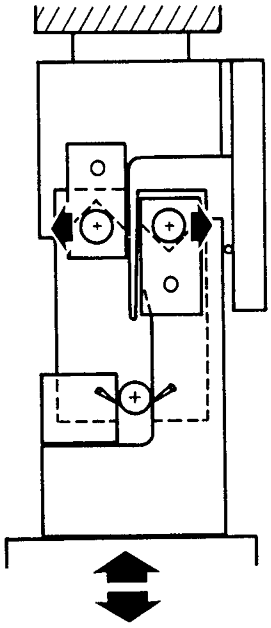
Reversed loading, or loading the specimen through zero load, may also be accomplished by modifying the testing fixture as shown on the right (Buzzard, 1988). Adding the loading pin retainer straps allows a tensile load as well as a compressive load to be applied. Rotation of the specimen when under reversed loading is prevented by adding a block at the lower loading pin.

Both of these modifications may be incorporated simultaneously if so desired.

MODES I AND II MIXED



MODE II REVERSED



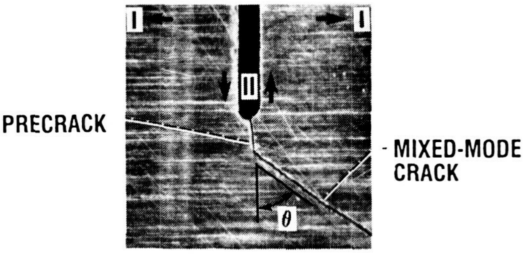
CD-88-31746

MIXED-MODE TESTING

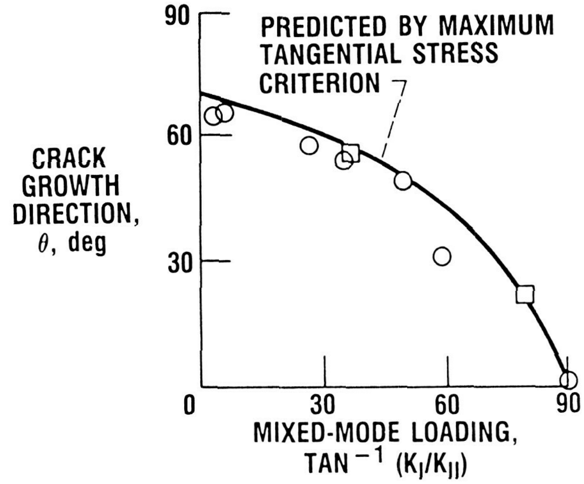
A knowledge of the mode I and mode II fracture characteristics of a material is essential to understanding failure initiation in a structure made of that material and subject to mode I and mode II loading. However, failures in a structure rarely progress by either of these two modes alone, but rather by a combination of modes. It therefore becomes necessary to obtain data that describe the mixed-mode fracture properties of structural materials. Such data have been recently obtained by Buzzard for hardened M-50 bearing steel and are presented below.

The plot at the left shows the path taken by a crack under various combinations of mode I and mode II loading to failure. Experimentally obtained data agree well with values predicted by the maximum tangential stress theory. Under mixed-mode loading the fracture path ranges from 0° to about 70° from the tip of the precrack toward the tensile-loaded leg of the specimen. The photograph shows a typical cracked M-50 steel specimen that fractured at an angle of about 65° under mixed-mode loading.

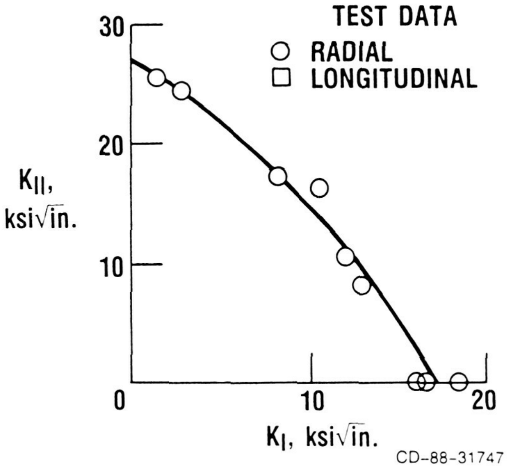
The plot at the right shows the relative amounts of K_I and K_{II} at fracture for this series of tests.



CRACK PROPAGATION DIRECTION AS FUNCTION OF K_I/K_{II} RATIO FOR M-50 BEARING STEEL



STRESS INTENSITY AT FRACTURE FOR MIXED MODES I AND II IN M-50 BEARING STEEL



CD-88-31747

REFERENCES

Buzzard, R.J., Gross, B., and Srawley, J.E., 1986, "Mode II Fatigue Crack Growth Specimen Development." ASTM STP 905.

Buzzard, R.J., Succop, G., and Gross, B., 1987, "Mode II Test Specimen and Method." NASA Tech Brief No. LEW-14281. NASA Tech Briefs, Vol. 11, No. 3, pp. 55-56.

Buzzard, R.J., and Gross, B., 1988, "Calibration of a Mode II Test Specimen." ASTM STP 945, March 30, pp. 1083-1088.

Buzzard, R.J., 1988, "Mode II Fatigue Testing Apparatus." NASA Patent Application LEW 14124-1.

Ghosn, L., 1988, "Crack Propagation in Roller Bearings Using the Boundary Integral Equation Method - A Mixed-Mode Loading Problem." ASME Journal of Tribology, vol. 110, July 1988.

Gross, B., Buzzard, R.J., and Brown, W.F., Jr., 1986, "Elastic Analysis of a Mode II Fatigue Crack Test Specimen." International Journal of Fracture, pp. 151-157.